COLD WATER BYPASS AND FIRING RATE CONTROL

Field

The present invention is related to the field of hot water boilers, and more particularly, to control systems for high efficiency condensing hot water boilers or water heaters.

Background

Recent advances in boiler technology have yielded high efficiency condensing boilers. A high efficiency condensing boiler has a primary heat exchanger and a secondary heat exchanger. Circulating fluid (such as return water) going through a high efficiency condensing boiler typically passes through the secondary heat exchanger and then enters the primary heat exchanger. The primary heat exchanger receives heat from burning fuel, while the secondary heat exchanger receives exhaust fumes from the primary heat exchanger for heat exchange with the circulating fluid. A temperature sensor sensed the circulating fluid entering the secondary heat exchanger and may be referred to as an "inlet" or "return" fluid temperature sensor. Circulating fluid entering the primary heat exchanger is monitored by another temperature sensor that is referred to as a "bypass" temperature sensor.

In many high efficiency condensing boilers, condensation in the primary heat exchanger can cause damage to the internal components of the primary heat exchanger. In such boilers, condensation should minimized or prevented in the primary heat exchanger. Condensation is typically allowed to occur in the secondary heat exchanger, as the secondary heat exchanger is often constructed to withstand such condensation. In many cases, and to help minimize or prevent condensation from occurring in the primary

heat exchanger, it is often desirable to keep the bypass water temperature above some minimum temperature.

The secondary heat exchanger typically causes, at most, about a ten degree rise in temperature of the returning fluid passing there through. To help keep the bypass temperature above the desired level, some high efficiency condensing boilers provide a bypass system that often includes a bypass valve that can be opened or closed, as needed, to maintain the bypass temperature at the boiler input by routing fluid leaving the primary heat exchanger back to the inlet to the primary heat exchanger.

Some applications include using a high efficiency condensing boiler to heat water that is supplied to circulation pipes under a sidewalk or driveway in cold climates (for example, to remove or prevent ice buildup). In such applications, hot water is supplied to the circulation pipes by the boiler, but a significant amount of heat is removed from the water before the water is returned to the boiler. As such, the water temperature at the inlet of the primary heat exchanger can be quite low, making it more difficult to maintain the bypass water temperature above the minimum temperature value in a robust and efficient manner.

Summary

The present invention, in a first embodiment, provides methods of controlling a boiler system. One illustrative method includes controlling the bypass temperature by increasing the firing rate of the boiler. Further methods include bypass temperature

5   control methods wherein both regular and fast control methods are used, where the regular method operates to control bypass temperature by using, first, a bypass valve, and second, possible increases in firing rate. The fast control method responds to particular situations indicating potential condensation in a primary heat exchanger to increase firing rate without waiting for a bypass valve to fully open. Further embodiments include

10   controllers programmed or containing programming for performing steps of the method embodiments.

Brief Description of the Drawings

Figure 1 is a schematic illustration of a high efficiency condensing boiler system;

15   Figure 2 is a block diagram representing dual modes for bypass control;

Figure 3 is a block diagram for an illustrative method; and

Figure 4 is another block diagram for an illustrative method.

Detailed Description

The following detailed description should be read with reference to the drawings. The drawings, which are not necessarily to scale, depict illustrative embodiments and are not intended to limit the scope of the invention.

5   While much of the following detailed description focuses on an embodiment having one boiler, it should be understood that for multi-boiler systems, there are several manners for incorporating the present invention. If multiple boilers are used in parallel, then each boiler in the system may separately include a controller adapted to perform the methods which follow. Further, with multiple boilers, a single controller may adapt the

10   following methods to enable a single boiler to have an increased firing rate for preventing condensation in other boilers, if so desired. If several boilers are used in series, then the following methods focus primarily on the goal of protecting the first boiler to receive returning water, as later boilers in the series should receive water at higher temperatures due to the work done by the first boiler in the series. As used herein, a heat exchanger

15   intake indicates the portion of a heat exchanger for receiving a circulating fluid in order to heat the circulating fluid.

While the following detailed description discusses, primarily, water as the circulating fluid, any suitable fluid may be used for these methods, and if water is the circulating fluid, any desired or suitable additives may be used as well.

20   A boiler itself operates having certain inherent characteristics and may be roughly modeled as a second order responsive system. For example, the boiler receives a signal for more heat and there is a delay before added heat is provided, and alternately, when sufficient heat has been provided there is a delay before the boiler stops producing such

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added heat. Most proposed solution methods are or are similar to proportional/integral control methods, which are second order methods having three solutions: overdamped, underdamped, and critically damped. Designs are usually formulated for underdamped responses having sufficient damping to attenuate overshoot relatively quickly.

5   A problem recognized here is that the typically desired proportional/integral response, while illustrating an underdamped response, still attenuates quickly, since wide heating swings over time are undesirable. However, given a large input perturbation, the ordinarily desired damping can prevent adequate response to prevent condensation damage in the primary heat exchanger. Therefore, in the following illustrative

10   embodiments of the present invention, a second, faster (less damped) response method is applied in parallel with a first response method, where the second response method provides a response only under certain conditions where it has been identified that there is a potential for damage if an input perturbation occurs. Some of the following embodiments use a second variable in place of that ordinarily used in the boiler control

15   method by referring to the inlet temperature rather than the bypass temperature.

In several embodiments, the second formula, when brought into use, controls the boiler firing rate. In one such embodiment, the first formula is used to control the bypass valve, partly because faster control of the bypass valve is limited by the bypass valve itself. For example, the bypass valve may be relatively slow to respond, taking several

20   minutes to move from fully closed to fully open. Modifying the firing rate, in contrast, can create a more dramatic increase in bypass temperature more quickly. In the illustrative example, the second formula does not wait for modification of the bypass valve position, instead going to a change in firing rate in response to an identified set of

circumstances which the first method may not be capable of resolving adequately. For systems such as those illustrated in U.S. Patent No. 6,694,927 to Pouchak et al., which is incorporated herein by reference, the relatively slow changes in bypass temperature effected by modification of the bypass valve position operate as a damping mechanism,

5   slowing response and limiting overshoot.

The following illustrative examples show "fast" responses using firing rate modifications. One reason for focusing on the firing rate rather than the bypass valve for the fast response is that the effect that raising the firing rate has on bypass temperature is more dramatic than the effect that can be had by opening the bypass valve further. In

10   some systems, a small change of firing rate can have a greater effect on the bypass temperature than a complete change from full closed to full open of the bypass valve.

Figure 1 is a schematic illustration of a high efficiency condensing boiler. The system includes a pump 12 moving water through a primary heat exchanger 14. Flue gasses 17 from the primary heat exchanger 14 are directed to a secondary heat exchanger

15   16 placed in the return water path for the system. Firing rate and flue gas flows are controlled, in part, using a combustion/purge blower 18. The firing rate may also be controlled using various valves for controlling fuel flow, air/fuel mixing devices, and other control mechanisms (not shown). A bypass valve 20 is used to direct output water back to the return flow before it enters the primary heat exchanger 14, as needed. Several

20   sensors 22, 24, 26 relay signals to a controller 28. The controller 28 controls several system components including the pump 12, blower 18, and bypass valve 20, as well as other boiler components such as gas control valves, air/gas mixers, etc.

For the purposes herein, the sensor that is prior to the secondary heat exchanger 16 is referred to as the inlet sensor 24. The sensor that is between the secondary heat exchanger 16 and the primary heat exchanger 14 is the bypass sensor 26. The sensor after the primary heat exchanger 14 is the output sensor 22. If the temperature sensed by

5   the bypass temperature sensor 26 is too low, the bypass water temperature may be low enough to cause condensation in the primary heat exchanger 14. In response to the bypass temperature sensor 26, the bypass valve 20 may open to a greater degree to allow output water to feed back to the return flow and warm the temperature sensed at the bypass sensor 26. If the bypass valve 20 is already fully open, the firing rate of the boiler

10   may be adjusted to increase its heat output..

The combustion/purge blower 18 may be a variable frequency drive unit that can help provide a variable firing rate for the boiler. When the variable frequency drive of the blower 18 operates at a high level, the blower 18 increases the heating output of the boiler, as well as forcing a greater amount of flue gasses 17 to the secondary heat

15   exchanger 16. During operation, the secondary heat exchanger 16 warms inlet water before it enters the primary heat exchanger 14. As flue gasses 17 pass through the secondary heat exchanger 16, condensate can form inside the secondary heat exchanger 16, which is designed and adapted to handle condensation without resulting in excessive corrosion.

20   Figure 2 is a block diagram representing dual modes for bypass control. The control begins by observing the output of a bypass temperature sensor 50 and continues with parallel determinations in an regular block 52 and a fast action block 53. The regular block 52 is the one which is used most of the time for bypass control. In the

regular block 52, the bypass temperature sensor 50 provides an output that is compared to a bypass setpoint 54, shown as comparison 56.

The comparison 56 yields an error signal that is sent to bypass control 58. The bypass control 58 observes the rate of error change and the actual error and uses an error derivative look-up table to determine whether to call for additional or less bypass warming. This control signal is sent to a bypass valve control 60 that the causes the bypass valve 62 to open or close (or remain in position). A floating valve output synch 64 is periodically used to re-synch the bypass valve 62, and can periodically call for the bypass valve 62 to be opened or closed for synchronization purposes.

A bypass position observation block 66 monitors the bypass valve 62 and its movements to provide data related to the extent to which the bypass valve 62 is open. In some systems, the bypass position observation block 66 determines how much the bypass control 58 has requested opening of the bypass valve 62. If the bypass valve 62 reaches a state of 100% open, the bypass position observation block 66 will indicate to output logic 68 that the bypass valve 62 cannot open further, yet bypass control 58 is continuing to call for more bypass warming. In response, the output logic 68, in some systems, can increase the firing rate call it sends to the blower (not shown) and other boiler controls.

The signal to increase firing rate may occur as soon at the 100% valve open level is reached, or may wait for a threshold of some sort, before making such a call. A "threshold" for increased firing rate may take many forms. For example, if the 100% level is exceeded for a certain period of time or by a certain amount, or by a sliding scale accounting for both the period of time and the amount of excess, the "threshold" may be breached. In place of a threshold, some other factor may be considered, for example, if

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the time elapsed from a 90% level to reaching the 100% level is below a certain amount. As noted above, increasing firing rate can affect the bypass temperature in a more dramatic fashion than adjusting the bypass valve 62.

However, changing firing rate results in reduced system efficiency, since the

5   system operates at a higher level than needed for the purposes of heating and may cycle more frequently. Further, the higher firing rate can cause an increase in the variance of output temperatures and system temperatures around a setpoint, where such variation may be exaggerated beyond what it would otherwise be. Therefore, for situations that are determined to be relatively safe, adjustments to the bypass valve 62 may be performed

10   first, and if those adjustments fail to keep the bypass temperature up, then the firing rate may be adjusted.

The fast block 53 may provide another signal in response to changing or potentially damage-causing situations. For example, as the bypass control 58 calls for additional bypass warming of return water, it will first call for opening of the bypass

15   valve 62 until it reaches 100% open, after which the bypass position observation 66 will pass along a signal to the output logic 68 calling for (or causing the output logic 68 to determine it is necessary to call for) increased firing rate. The example fast block 53 can call for increased firing rate earlier because it does not wait for a determination that the bypass valve 62 cannot open further.

20   The following is an illustrative example of how one may perform the steps within the fast block 53 to determine if a higher firing rate should be requested. An integral action logic block 70 takes several pieces of data. First, the output of the bypass temperature sensor 50 is observed, as well as the inlet temperature 72 taken from an inlet

temperature sensor (not shown). Two constants, the condensing temperature 74 and the

bypass setpoint 54, are also observed. Preferably the bypass setpoint 54 is set higher than

the condensing temperature 74.

The pseudocode for the illustrative example method goes as follows (noting that

5   the temperatures are in degrees Celsius):

$$IF[(Bypass\_Temp < Bypass\_Setpt + 5)AND(K1\_Term != 0)]$$

$$THEN: \begin{bmatrix} CWD\_Term\_1 = \dfrac{(T_{CONDENSE} - T_{INLET}) * K1\_Term}{K3\_Term}; \\[2mm] if(CWD\_Term\_1 < 0, then(CWD\_Term\_1 = 0); \\[2mm] CWD\_Term\_2 = \dfrac{Bypass\_Setpt - K4\_Term - Bypass\_Temp}{K2\_Term}; \\[2mm] CWD\_Int\_Act = \lim(-30,100, CWD\_Int\_Act + CWD\_Term\_2); \\[2mm] CWD\_Total\_PID = \lim(0,100, CWD\_Term\_1 + CWD\_Int\_Act; \end{bmatrix}$$

$$ELSE: \begin{bmatrix} CWD\_Int\_Act = 0; \\ CWD\_Total\_PID = 0 \end{bmatrix}$$

The acronym CWD indicates a cold water derivative, as in a factor derived from cold

water characteristics for the purposes of aiding in the illustrative method. The

pseudocode terms are defined as:

10   Bypass_Temp: Temperature measured at the bypass temperature sensor,

where bypass water has mixed with return water and after the secondary

heat exchanger but before the primary heat exchanger.

Bypass_Setpt: Desired temperature for the bypass temperature. Typically

about 54 degrees Celsius (130 degrees Fahrenheit).

15   K1_Term: A constant term used for the fast acting control. In the

illustrative example, K1_Term = 4.

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CWD_Term_1:   An error indicator determined directly from the inlet

temperature. Also referred to as the proportional inlet error.

$T_{CONDENSE}$:   Reference temperature below which condensation is

assured to occur inside the primary heat exchanger; minimum temperature

for water entering the primary heat exchanger; minimum desired bypass

temperature. Typically set to about 44 degrees Celsius (111 degrees

Fahrenheit). Condensation often begins to occur at higher temperatures

than this, however, the low temperature selected would assure

condensation and may prevent over-use of the firing rate increase.

T_{INLET}:   Measured temperature in the circulation flow before the

secondary heat exchanger is encountered. Note that before the fluid enters

the primary heat exchanger it will be warmed by both the secondary heat

exchanger and, usually, at least some mixing with water fed back through

the bypass valve.

K2_Term: Another constant term used for the fast acting control. In

the illustrative example, K2_Term = 0.8.

CWD_Term_2:   A current error term derived from the present bypass

temperature and used in the integral term.

CWD_Int_Act: An integral (summing) error term derived from

CWD_Term_2. May be called the integral bypass error.

CWD_Total_PID: The composite error term determined from the proportional

inlet error and integral bypass error.

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K3_Term: A scaling factor, for the illustrative example K3_Term is

about 8.

K4_Term: A scaling factor, for the illustrative example, K4_Term is

about 3, in degrees C.

5   Returning to the pseudocode, the first IF statement determines whether the bypass

temperature is in a range where checking on the fast acting control is even necessary. If

the bypass temperature is more than five degrees higher than the bypass setpoint, there is

no need to check on the fast acting control because conditions are well within safe

bounds.

10   The part of the IF statement that follows the AND function checks whether the

system is enabled; for the illustrative example, a user may change the value of K1_Term

to adjust the control method response and/or to disable the system. As shown, if

K1_Term is set to zero, then the firing rate bypass system has been disabled by a user.

Instead of checking the K1_Term, an alternative embodiment may use a different

15   variable or check to see if the system is enabled, for example, a toggle switch. It should

be noted that for the pseudocode, the != symbol indicates that the two variables on either

side of the symbol are not equal.

Assuming the "IF" condition is met and the system is enabled, the method

performs several additional steps. A first term, CWD_Term_1 is directly related to the

20   inlet temperature. If the inlet temperature is less than the condensation temperature for

the boiler itself, then the CWD_Term_1 immediately reflects this fact. The K1_Term

and the divisor (K3_Term) scale CWD_Term_1. These scaling factors may of course be

modified for various applications to provide greater or lesser speed. By increasing

CWD_Term_1 using either scalind term, one would increase the speed at which the method embodied in the pseudocode responds as well as the extent to which it modifies firing rate, if needed.

As shown, the CWD_Term_1 is set to zero if the calculation of CWD_Term_1

5   yields a negative result. Next, a CWD_Term_2 is calculated from the bypass temperature setpoint, the bypass temperature, and two scaling factors, the K2_Term and the K4_Term. CWD_Term_2 acts as a present "error" term relating to the bypass temperature, rather than the inlet temperature. The K2_Term, as noted above, is set to be 0.8, meaning that it amplifies the linear error if the bypass temperature gets too far away

10   from the bypass setpoint. The K4_Term, also as noted above, is set to about three degrees Celsius, and may be adjusted to modify the bypass temperature level at which the system begins integrating for the CWD_Int_Act term.

Next, a CWD_Int_Act term is calculated from the CWD_Term_2. The CWD_Int_Act term is an integral action term that integrates the ongoing error noted by

15   the use of CWD_Term_2. As shown, both positive and negative limits are included for CWD_Term_2. This prevents CWD_Term_2 from accumulating a too large negative or positive value that dominates the CWD_Term_1 in later calculations.

Finally, the CWD_Total_PID value is set as shown. Again, high and low limits are given. The value given, within the limits, is the sum of the immediate error taken

20   from the intake temperature (not the bypass) represented by CWD_Term_1 and the integral action error taken from the bypass temperature represented by CWD_Int_Act.

Next, the firing rate control is dealt with as follows:

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$$IF : [CWD\_Total\_PID > Total\_PID\_Error];$$
$$THEN : [Main\_Heat\_Command = CWD\_Total\_PID];$$
$$ELSE : [Main\_Heat\_Command = Total\_PID\_Error]$$

The pseudocode uses Total_PID_Error as the total error calculated using a more regular method such as the regular method 52 shown in Figure 2. The Main_Heat_Command provides a signal to indicate whether the bypass control calls for an increase in firing rate.

The output logic block 68 also receives a signal from individual stage heating command 80, which relays to the output logic block 68 the amount of heat load that the individual stage of heating (i.e. a single boiler being controlled) is being called upon to provide. For a single boiler system, the individual stage heating command 80 may be simply a thermostat call indicating whether heat is needed. A variety of controllers and methods may be used to provide a signal indicative of the heat load required from the individual boiler.

A summary of the above steps can be explained as follows:

1. Observe whether the boiler bypass temperature is in a range where fast response to a change in cold water input may be needed.

2. If so:

A. Observe the inlet temperature and compare the inlet temperature to a condensation reference temperature, looking for immediate potential problems and generating an error value based on the current inlet temperature; and

B. Observe the bypass temperature to generate an integral error that accumulates with time when the bypass temperature is more than an allowed amount below the bypass setpoint.

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3.   Then, combine the current inlet error value and the integral bypass

temperature error to create a signal indicating whether the firing rate should be

increased.

4.   Finally, use the firing rate increase signal from step 3, in

5   combination with an existing heat load signal, to determine the desired firing rate

for the system.

Figures 3 and 4 are block diagrams showing steps of two illustrative methods.

Figure 3 illustrates a method of controlling firing rate to meet a heat load and avoid

condensation. A heat load signal is received, as shown at 100, and the firing rate is then

10   set to provide a heat output for the boiler to meet the heat load, as shown at 102. Next,

the risk of condensation is assessed, as shown at 104. If the risk is acceptable, as shown

at 106, the method recycles back to wait to receive another heat load signal as shown at

100. If the risk is not acceptable, as shown at 108, the method continues to increase the

firing rate to reduce the risk of condensation, as shown at 110. By increasing the firing

15   rate as shown at 110, the method increases the heat output of the boiler to a level beyond

that needed to meet the heat load in order to prevent condensation.

Figure 4 illustrates another method for controlling condensation risk having two

control sub-methods. Again, as shown at 200, the method begins by receiving a load

signal, and setting the firing rate for the load, as shown at 202. Next, the circulating fluid

20   temperature is monitored as shown at 204. The circulating fluid may be monitored at one

or more locations, for example, for inlet, output, or bypass temperature.

The two control methods may operate in parallel, or may be incorporated to a

controller that operates one method and then the other as callable subroutines in software,

for example. A first control method starts at 206 with a determination of whether condensation is likely or unlikely. The determination may be, for example, a comparison of a measured temperature to a setpoint, or a comparison of a measured temperature and rate of change to some other value. If condensation is likely, as shown at 210, the

5   method continues to check the bypass valve as shown at 212. If the bypass valve is not fully open, as shown at 214, the method continues with a bypass valve adjustment, as shown at 216. After adjustment of the bypass valve (e.g. opening the bypass valve), the method goes on to a return block as shown at 218, which goes back to wait for a next iteration.

10   Working backwards from the bypass valve adjustment shown at 216, if the check of the bypass valve 212 shows that the bypass valve is (or should be) fully open, as shown at 220, the method goes on to increase the firing rate, as shown at 222. Again, from the increase in firing rate at 222, the method goes on to the return block shown at 218. Going farther back, if the first control method determines that condensation is

15   unlikely, as shown at 224, the method simply jumps to the return bock shown at 218.

    A second control method also operates, as shown at 226. If the second control method determines that condensation is unlikely as shown at 224, the second control method bypasses other steps and goes to the return block. If the second control method 228 determines that condensation is likely, as shown at 228, the second control method

20   simply increases the firing rate, as shown at 230, and continues to the return block at 218.

    It should be noted that the second control method does not wait for the bypass valve to be fully open. As such, the second control method is a "fast" method which goes directly to the step of increasing the firing rate. Meanwhile, the first control method 206

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can be referred to herein as an "ordinary" control method since it takes a more deliberate approach and does not directly go to the step of increasing firing rate.

One of skill in the art will understand that the present invention may also be manifested in a controller for controlling a boiler, the controller adapted for performing the methods explained above. In one such embodiment, a controller (such as controller 28 in Figure 1) includes a set of instructions stored on a readable medium for performing the above steps. The readable medium may be, for example, an electrically, magnetically, or optically readable medium. The controller may contain any number of logic circuits or components and may include a microcontroller or microcomputer.

While adding to the physical complexity of the system, an alternative (either separate or for use in conjunction with the above methods) is to include a second bypass valve adapted for quickly opening and closing in response to a stimulus. The purpose of the second bypass valve would be to provide an immediate, yet coarse, response for boiler protection, and would be an extraneous part the majority of the time. Therefore a cheap on/off valve would be used for a second bypass valve, the on/off valve lacking precise or accurate intermediate levels. For example, a valve having three settings: full on, half on, full off, could be used for a second bypass valve when bypass temperatures drop beyond a safe limit.

Those skilled in the art will recognize that the present invention may be manifested in a variety of forms other than the specific embodiments described and contemplated herein. Accordingly, departures in form and detail may be made without departing from the scope and spirit of the present invention as described in the appended claims.

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